CONFERENCE SUMMARY

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Abstract.
At the end of three days' spirited discussion of the type 2 Seyfert galaxy NGC 1068, what do we think we understand about this object? New observations particularly in the infrared and radio are helping to resolve old problems, while drawing attention to new ones. It appears that NGC 1068 is a relatively normal spiral galaxy in which large-scale gravitational disturbances are funneling matter into the nucleus. A collimated outflow disturbs the interstellar medium out to kiloparsec scales, but the nucleus itself is hidden behind an opaque screen. Radio observations have now pierced the screen, and suggest that at the center of it all, a 10 20 million solar mass black hole is accreting at close to its Eddington limit.

1. Introduction

Few galaxies have been so thoroughly scrutinized, at so many wavelengths, that one can fruitfully devote an entire three-day workshop to them. NGC 1068 is such a galaxy. NGC 1068 may not be quite the stuff of poetry (see, e.g., *Cygnus A* by D. M. Thomas, the more presentable parts of which are quoted by Roger Blandford in Carilli & Harris 1996), but about 50 of us managed to wax lyrical over it for three days at Ringberg Castle, in the Bavarian Alps.

As a scientist of rather limited shorthand skills, I despaired at capturing the rich texture of new observations and diagnostic techniques being brought to bear on this galaxy. Fortunately, the meeting was a true workshop, characterized by extensive and freewheeling discussion at every stage. In this summary, I try to convey the general tone of the discussions along with the individual contributions that particularly caught my attention.

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2. AG or AGN?

It is the bright and complex nuclear region that attracts us to NGC 1068. But what is the setting for these pyrotechnics? Is it appropriate to decouple our study of the active galactic *nucleus* (AGN) from that of the surrounding galaxy? Or must we consider the entire *active galaxy* (AG) as a unit, with complex interactions operating among all scales.

To a first approximation, the active nucleus seems to reside in the middle of an otherwise normal galaxy. We heard little mention of possible environmental triggers for activity such as mergers or tidal encounters with other galaxies because there is little or no evidence for such interactions. Perhaps such an interaction occurred long ago; if so, the outer galaxy has since returned more or less to normal. Perhaps we should not be too surprised, since HST observations of more luminous distant quasars show that some of them are also seemingly isolated and undisturbed (Bahcall et al. 1996).

But there is evidence suggesting that the nucleus is fuelled by inflow of interstellar gas through the galaxy. At large scales, the clues are subtle. The HI distribution in NGC 1068 seems unusual for its Hubble type [Brinks]. The HI surface density tracks the optical surface brightness, instead of being more extended, and the rotation curve gently declines outward. Has interstellar gas from the outer galaxy been drained into the center? It is dubious that the amount of gas involved could have been enough to skew the overall degree of mass concentration in the galaxy, and thus account for the declining (rather than flat) rotation curve. Perhaps NGC 1068 was born with a slightly more concentrated mass distribution, and a slightly greater proclivity for gravitational instability, than a typical spiral. Once triggered, gravitational instability could be enhanced by dissipation in the gas, as in the "bars within bars" scenario for fueling AGNs (Shlosman et al. 1989).

There is both kinematic and morphological evidence that the inflow is driven by large-scale nonaxisymmetric gravitational disturbances. Brinks reported redshifted HI absorption, and the trend continued to smaller scales with observations of molecules [Tacconi, Scoville, Lutz, ...]. Indeed, both molecular gas and stars (as viewed in the IR) seem to trace out a bar, on sub-kpc scales, with trailing spiral shocks just as predicted by theorists [Dehnen]! Plausibly, this inflow feeds both star formation and the AGN, but in a curiously orderly way. Perhaps suggestions that powerful AGNs would be associated with severe disturbances on all scales were overly alarmist.

3. Starburst(s)

Vigorous star formation is observed "out in the open" in NGC 1068 on kiloparsec scales, and may be significant as a tracer of gravitational instability and a source of the observed hydrodynamic turbulence in the atomic and molecular gas. But more attention was focused on the the more compact starburst that we can't see quite as well. Thatte described infrared observations of a central star cluster that is not too compact (40 pc), yet is distinct from the galactic bulge. The rate of star formation in this central region is unclear, and the contribution made by stars to the nuclear bolometric luminosity is equally uncertain.

These uncertainties are compounded by the very complex interactions between stars and gas [Terlevich]. Supergiants and massive stars recycle mass and energy between the stellar and gas distributions. When a large fraction of the energy output from a star goes directly into the gas, through stellar winds and supernova explosions, the radiative and morphological signatures can be quite different from those of a simple star cluster. If the gas distribution is aspherical, the "superbubble" excavated by the winds from massive stars can be collimated into a structure that resembles a jet. The moral? Be careful when interpreting organized gas flows.

4. The Radio Jet & NLR

Even more caution is in order when interpreting the effects of the nuclear activity on the interstellar medium. We do not know how much of the energy emerging in line emission from the narrow-line region comes from photoionization by the nuclear continuum, and how much is powered locally by an energetic outflow [Baum]. That there are important local interactions seems clear, however. Sharp bends and spot enhancements in the radio emission are suggestive of shocks as the outflow encounters interstellar clouds. Capetti and collaborators showed that the most intense regions of optical line emission seem to avoid the radio-bright structures in the kpc-scale plume; the idea that the radio-emitting plasma is pushing the line emitting gas around is reinforced by gas kinematic measurements [Cecil, Pécontal, Arribas]. The most intense interaction seems to be concentrated in a cone that is much narrower than the solid angle exposed to ionizing radiation, also suggesting that the additional energy injection by hot or fast-moving gas is crucial. The sharp contrasts in the cone do suggest "crepuscular rays" [Catchpole], but some sources of emission peeking around the clouds could be local rather than nuclear.

The evidence for direct interaction, unfortunately, does not tell us much about the physical nature of the radio-emitting region. Its energetics are barely constrained. Does the emission trace a jet, a jet's cocoon, or a bubble of shocked gas breaking out of the nucleus? Baum followed the radio observations inward, showing that the radio structure on scales of tens of parsecs resembles a well-collimated jet (Muxlow et al. 1996; Gallimore et al. 1996). A turbulent hypersonic jet driving radiative shocks into interstellar clouds forms the basis of Dopita's model (presented by D. Axon). In this picture, the photoionizing radiation is provided entirely by the cooling shocks.

The question remains whether there is enough energy in the outflow to power the narrow-line emission. At least one clue tending toward the affirmative is provided by evidence that most of the soft X-rays are produced over a kpc-scale region [Wilson]. Given that the electron scattering zone is far smaller, this suggests that the mechanical energy supply to the NLR is indeed substantial.

5. Smoke & Mirrors

The regions of gas (mirrors) and dust (smoke) which scatter and reprocess the central continuum provide the only way to observe the central ionizing continuum and broad emission lines (Antonucci & Miller 1985). Unsuccessful attempts to see through the obscuring gas in the infrared have only reinforced this conclusion [Ward, Glass].

Fortunately, the gas-rich environment of NGC 1068's nucleus provides many vantage points from which to view the nucleus, albeit indirectly. In addition to Antonucci & Miller's region of electron scattering along the radio axis, Cecil has identified mirrors to either side of the ionization cone, and Iwasawa reported on X-ray reflection signatures. ASCA observations of fluorescence lines from both "cold" (Fe I XVII) and "hot" (Fe XXV, XXVI) iron could provide important clues to the geometry and energetics of the close-in scattering zone, and Doppler shifts of the scattered BLR emission provide a diagnostic of the scattering zone's dynamics [Krolik]. The "smoke" is proving equally useful. The angular breadth of the cone of ionizing radiation is demonstrated by observations of the distant "NE Knot" [Bland-Hawthorn], while infrared measurements are mapping out the dust reprocessing and bipolar reflection nebula nearer the nucleus [Hough, Alloin, Pier].

The ambitious goal of reconstructing the spectrum and angular distribution of radiation escaping the nucleus from the scattered and reprocessed radiation has not yet been attained, despite the application of ingenious techniques. The most exciting new lines of attack involve recent infrared observations. The ISO infrared satellite has detected a wide range of ions around the nucleus [Lutz] requiring the predominant source of ionizing radiation to peak at 30 to 300 eV i.e., a quasar-like nuclear spectrum. Furthermore, molecular clouds which fall within the ionizing cones at 1 kpc radius show strong mid-infrared radiation but very weak line emission from polycyclic aromatic hydrocarbons (PAHs) [Bland-Hawthorn]. The latter are grains smaller than 10 Angstroms which are observed in terrestrial laboratories to be easily destroyed by X-ray radiation. The shape of the infrared spectrum, and the weak PAH emission, from the molecular clouds can be understood if the ionizing flux in these directions has a strong blue component, and is several times more intense ("beamed"?) than the reprocessed flux observed along our line of sight (Bland-Hawthorn & Voit 1993).

Of course, if a significant fraction of the ionizing radiation comes from outside the nucleus — from the starburst(s), or from auto-ionizing shocks or turbulent mixing layers associated with the jet — then working backward from the ionization structure to the incident continuum will be that much more difficult. Subtle analyses presented by Netzer, Sternberg, and Bland-Hawthorn are particularly sensitive to this.

6. The Central Engine

If any one group led us to the nucleus of NGC 1068, it was the radio astronomers. By the end of the workshop — and after much spirited debate — there was general agreement that the radio source labeled S1 marks the nucleus. S1 turns out to be a compact radio component resolved with the VLBA at several parsecs across, elongated approximately perpendicular to the base of the radio jet and with an "inverted" radio spectrum [Gallimore]. In contrast to luminous compact radio sources, where an inverted spectrum usually means a synchrotron self-absorbed source of high ($\sim 10^{11}$ K) brightness temperature, the brightness temperature of S1 is a few million degrees or less. Thus, it is probably free-free emission, perhaps from the inner surface of the obscuring disk or torus. The emission measure (and power required to ionize the gas) is quite large, and depends sensitively on the brightness temperature.

Greenhill's presentation of the latest observations of water masers provided the biggest surprise of the meeting. The blueshifted maser spots have now been mapped with VLBA and, as expected, lie on the opposite side of S1 to the redshifted masers. But they do *not* lie northeast of the systemic-velocity masers (which coincide with S1), symmetrically placed about the jet axis as they would be if tracing out the skin of a geometrically thick torus (Greenhill et al. 1996). Instead they trail off to the southeast, diametrically opposite the redshifted masers with respect to S1. The maser distribution looks generically similar to the warped disk traced out by masers in NGC 4258 (Herrnstein, Greenhill, & Moran 1996), but with a much more pronounced warp. The rotation curve is symmetric about S1 and fits that of an annulus, but the radial dependence of the velocity gradient is flatter than Keplerian, with $v \propto R^{-0.35}$. This is most easily explained as the dilution of the black hole's gravitational potential by an extended star cluster (or by the mass of the disk itself) but it could also reflect a steep dependence of the warp angle with radius.

Maser kinematics allow us to place a lower limit on the enclosed mass of about $2 \times 10^7\ M_\odot$, implying that the bolometric luminosity (mostly emerging in the infrared) is at least half the Eddington limit. Radiation pressure must be important, at least in the innermost accretion flow, and the accretion rate could be super-Eddington. The expected anisotropy of radiation from a super-Eddington accretion flow (Sikora 1981) could conceivably account for the degree of intrinsic beaming required by Bland-Hawthorn's analysis of the PAH emission and mid-IR reprocessed radiation.

But the strange geometry of NGC 1068's nucleus still resists explanation. Outside about 100 pc, interstellar gas seems to flow in an orderly fashion through the galactic disk. Why, then, should the inner accretion disk be so severely misaligned with the galaxy that both the axis of the ionization cone and the jet lie close to the galactic plane? Such misalignments are common in Seyferts, but nowhere else are they so clearly mapped. Not only are the maser disk and the S1 component both apparently misaligned with the galactic disk, but they are misaligned with one another as well.

On scales as large as a few parsecs, one cannot appeal to a misaligned black hole spin to alter the alignment of a disk through the Bardeen-Petterson effect (Bardeen & Petterson 1975). One possible explanation is that the fuel captured into the inner accretion flow consists of giant molecular clouds whose orbits have been randomized by gasdynamical or gravitational effects. One cloud of $10^5\ M_\odot$ could fuel activity in NGC 1068 for 10^5 years. But a pc-scale disk would probably require many such clouds to maintain an adequate accretion rate, given the usual estimates for accretion disk viscosity. The misalignment should then be much less pronounced, unless individual clouds have very large masses.

The newly discovered radiation-driven warping instability (Pringle 1996) would seem to provide the most promising explanation for the misalignments on parsec scales. A disk that is optically thick to both absorption and emission, illuminated by a compact radiation source at its center, is unstable to warping under the action of radiation pressure. This mechanism has been applied to the mild warp in the maser disk of NGC 4258, and may also explain the 164-day precession of the disk and jets in the Galactic X-ray binary SS 433 (Maloney, Begelman, & Pringle 1996)! Under certain conditions the magnitude of the warp may become extreme (Pringle 1996, private communication).

7. Concluding Remarks

Few prejudices about NGC 1068 were left unexamined during this intensive workshop, save for one. No one seemed to question that an opaque, dusty torus of molecular gas obscures our view of the central engine and broad-line region. Dynamical models for such a torus have long faced the difficulty of finding a mechanism that will support it against gravitational collapse to its orbital plane (Krolik & Begelman 1988). It is still an open question whether gravitational instabilities, magnetic effects, or some other form of stirring (e.g., by stellar winds) can overcome the dissipative tendencies of the gas. New evidence that NGC 1068 is radiating at close to its Eddington limit makes it more plausible that radiation pressure acting on dust could support the torus against gravity (Pier & Krolik 1992). But the distribution of maser spots on the sky is hard to understand as the manifestation of a torus. Moreover, if the maser emission is to be pumped by X-rays from the nucleus, the molecules must have a clear line of sight to the X-ray emitting region. Such a line of sight is provided naturally by a warped disk (Neufeld & Maloney 1995), which at the same time could obscure our view of the nucleus and restrict the solid angle of the escaping ionizing radiation. And severely warped, but geometrically thin, accretion disks no longer seem as far-fetched as they once did. We should not be surprised if the wonderful new observations and diagnostic techniques presented at this workshop force us to reevaluate even long-held ideas about NGC 1068.

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